Modeling Reconnection-driven Polar Jets from the Sun to the Heliosphere

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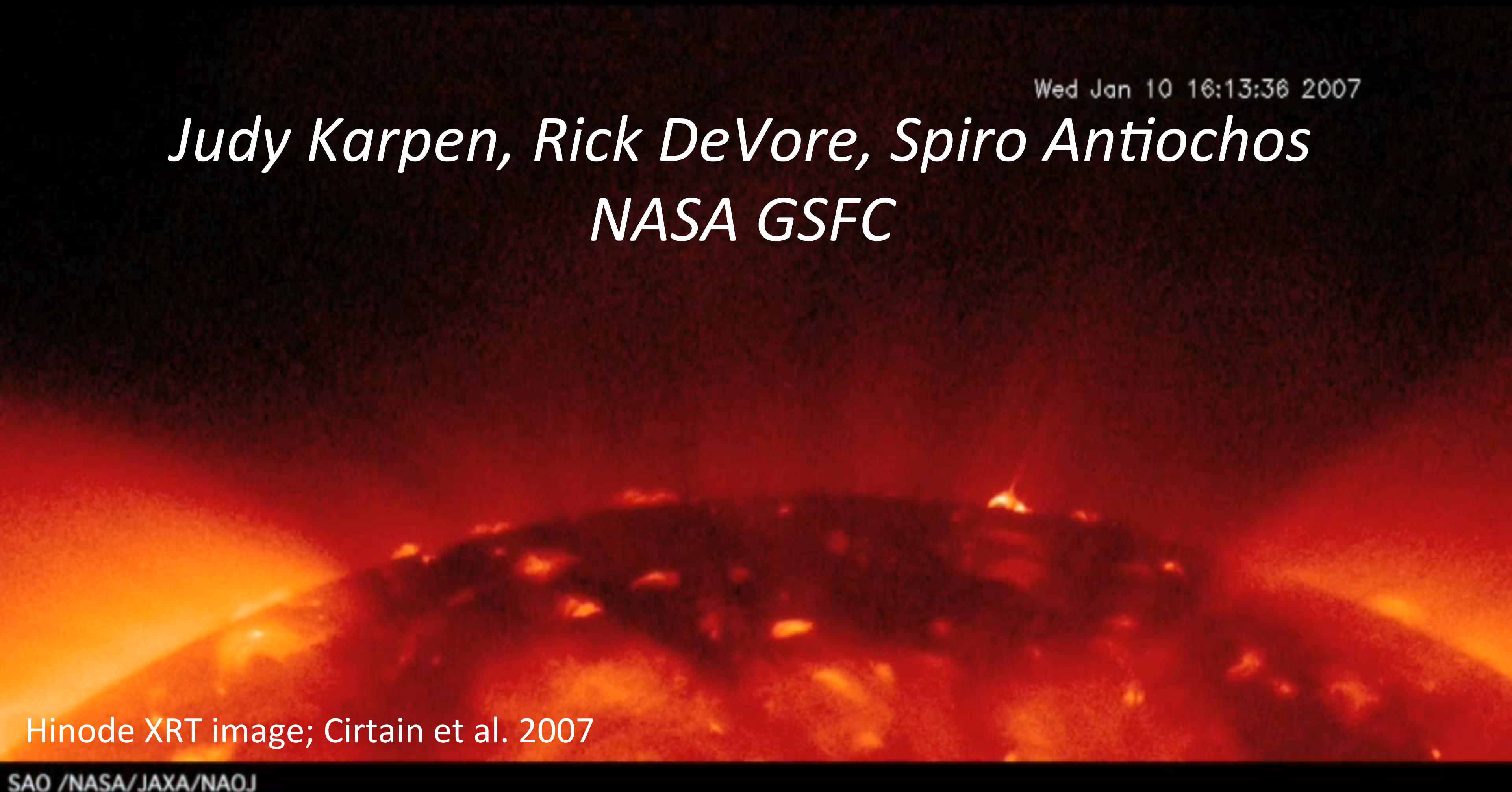


Hinode XRT image; Cirtain et al. 2007

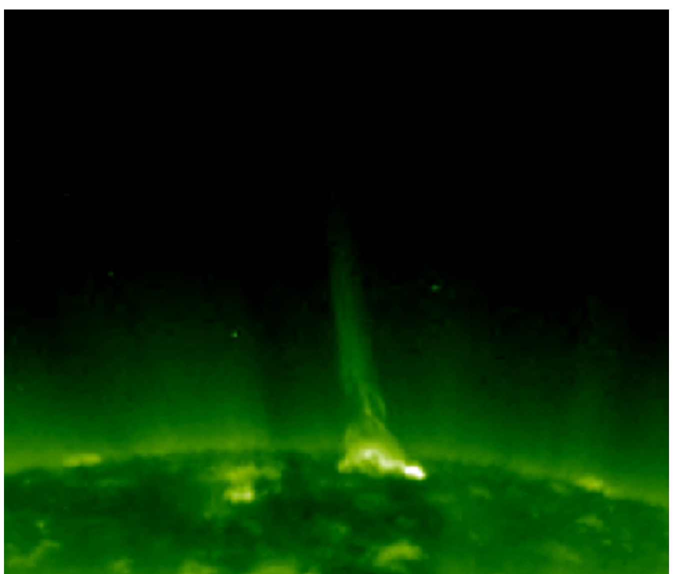
work supported by NASA's LWS TR&T program

Questions and Objectives

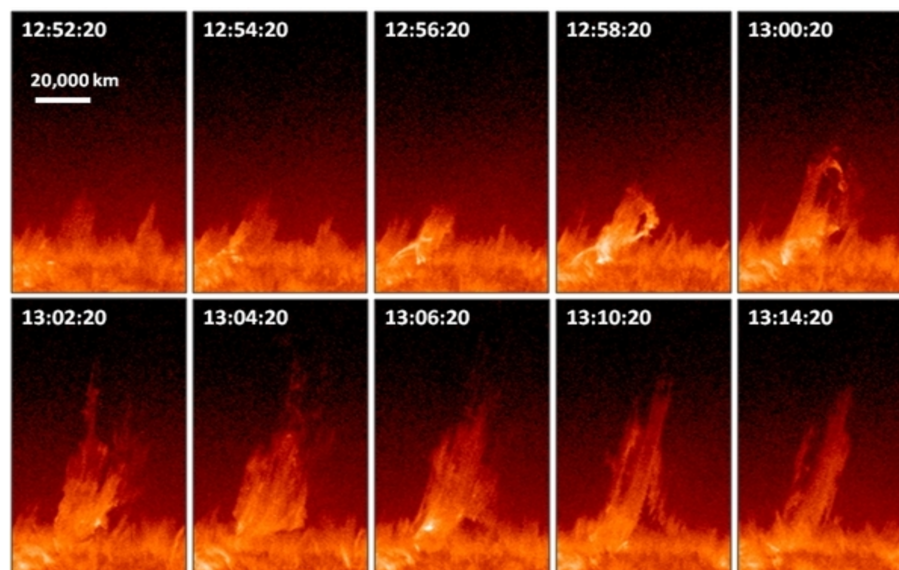
- Does reconnection drive polar jets?
  - establish the basic characteristics of 3D jets driven by reconnection at varying heights in coronal holes
  - predict jet and plume speeds and masses
  - measure upward and downward mass, momentum, energy, and helicity fluxes
- Does the energy released by reconnection heat the corona and accelerate the wind?
  - determine energy partitioning (bulk flow vs. waves) in the simulated jets and its geometry dependence
  - estimate frequency of jets needed to provide the observed energy/momentum flux to the corona/wind
  - test whether a quasi-steady wind can result from jets driven by continuous photospheric circulation

Observations

- Polar jets are observed in a wide range of emissions, from EUV and X-rays (e.g., EIT, TRACE, Hinode, and SDO) to optical and radio (e.g., LASCO, SECCHI), and possibly in IPS data.
- What heliospheric signatures could be detected by Solar Probe Plus and Solar Orbiter (*see Poster 203.02*)?



STEREO EUVI image *(Patsourakos et al. 2008)*

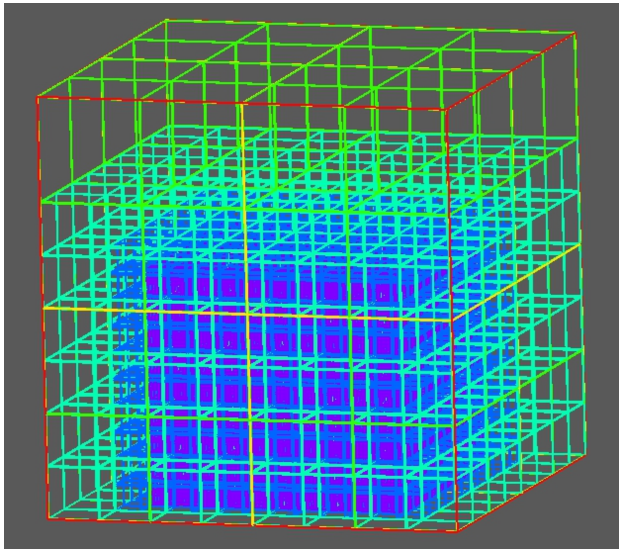


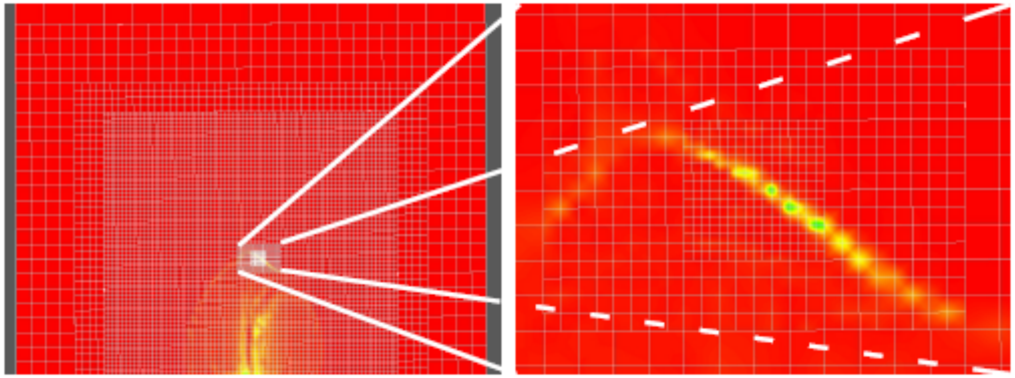
SDO/AIA 304Å image *(Moore et al. 2013)*

Methodology

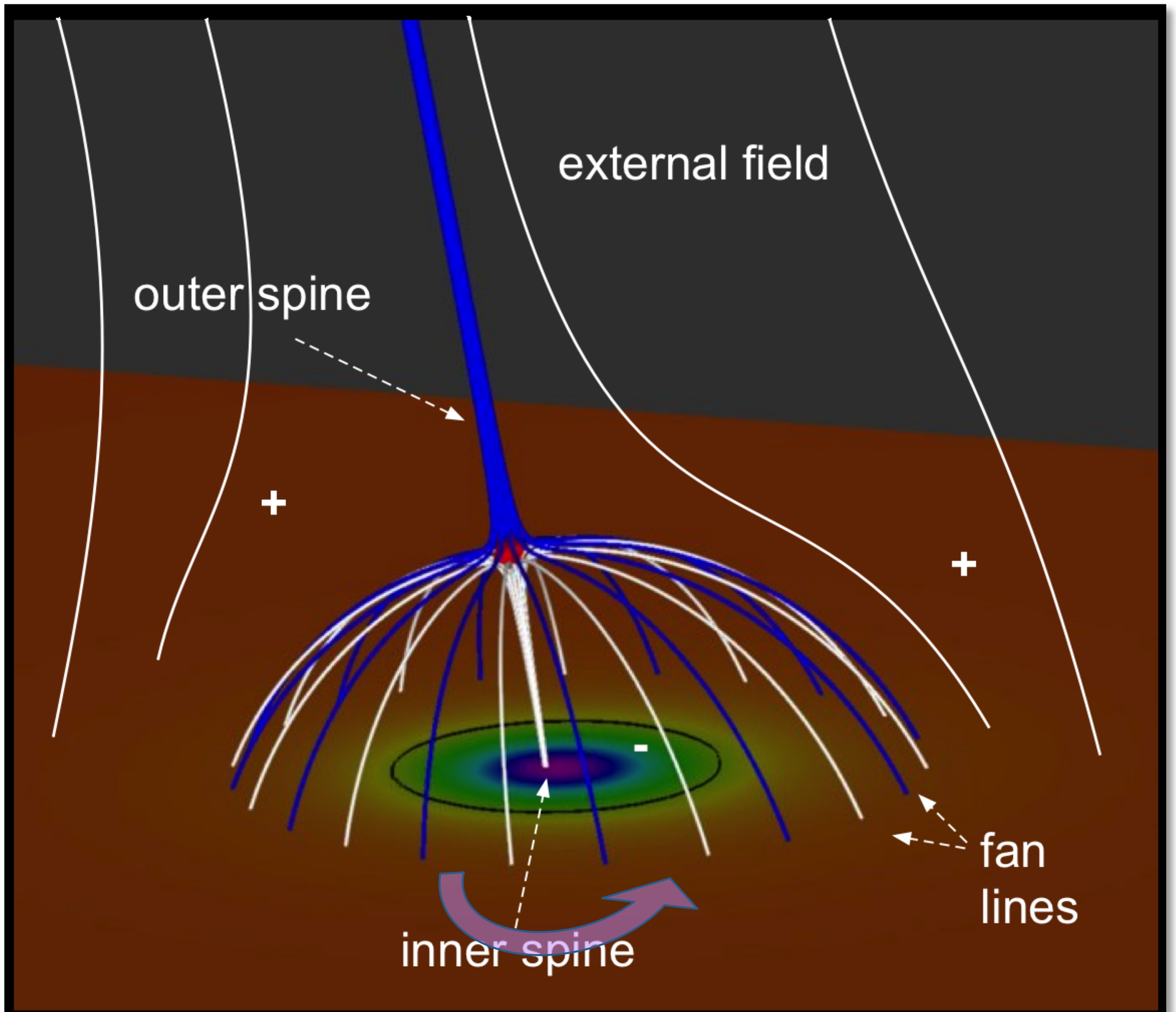
Simulate polar jets in an open corona with and without solar wind. Compare results with Hinode, SDO, and coronagraph observations of EUV, X-ray, and white-light jets. Predict heliospheric signatures for Solar Probe Plus and Solar Orbiter (*see Poster 203.02*).

- Numerical simulations employ the massively parallel Adaptively Refined MHD Solver (ARMS)
- Solves MHD equations using a monotone finite-volume method (DeVore 1991)
- Block-adaptive grids managed by PARAMESH **(**MacNeice et al. 2000**)** focus the finest resolution at thin current sheets





Physical Model



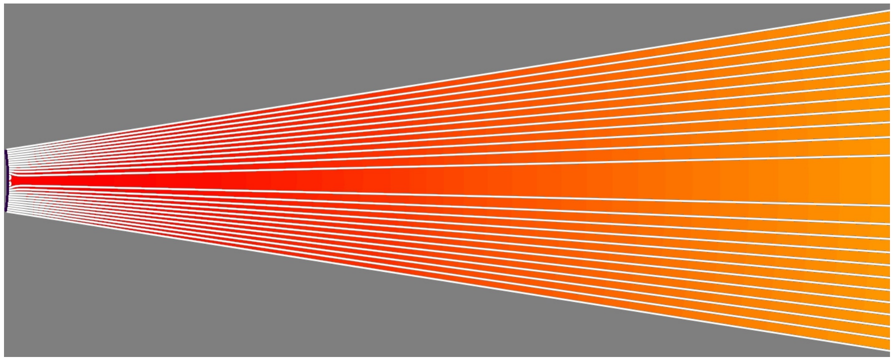
- Single embedded bipole in an open external field: “parasitic” polarity
- Subsonic rotational flows inside the polarity inversion line add free magnetic energy
- Slow reconnection at the mildly stressed null point precedes....
- Fast reconnection at the highly stressed null point and through the extended current sheet on the fan surface

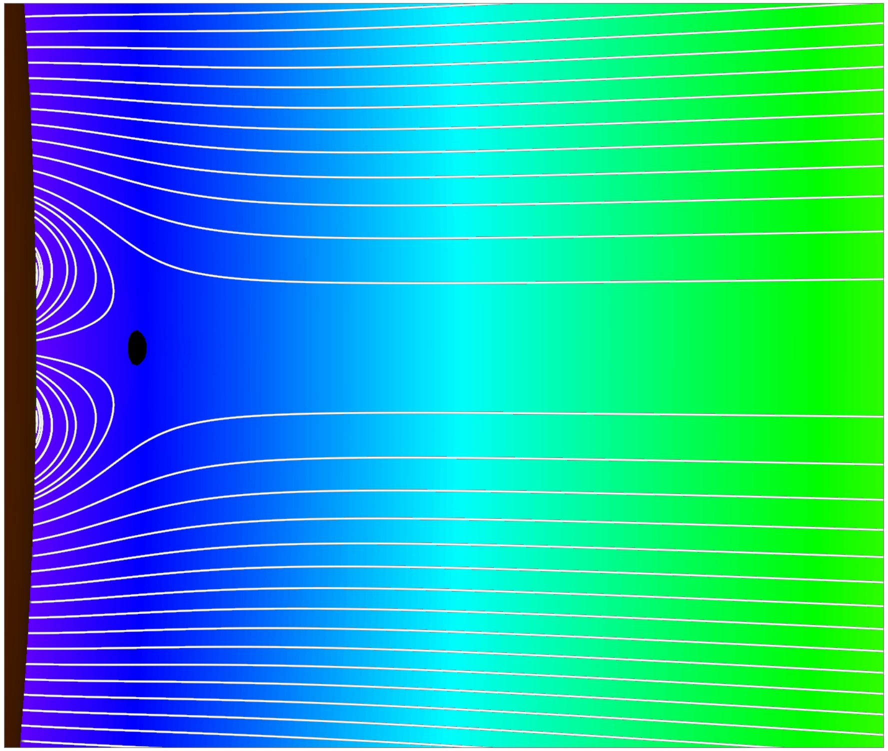
Modeling, Past and Present

- Previous Modeling (Pariat et al. 2009, 2010, 2015)
  - 3D Cartesian geometry
  - No gravity
  - Static atmosphere with uniform density and temperature
  - Closed lower boundary, open upper boundary
  - Adiabatic energy equation
  - Results: reconnection paradigm works but greater realism needed
- This Study: two cases
  - "Static" case: same as above with enhanced diagnostics
  - "Wind" case:
    - 3D Spherical geometry
    - Parker solar wind with stratified density (solar gravity)
    - Open inner and outer radial boundaries
    - Isothermal (no energy equation)
- Compare and contrast!

Movies will be shown when first author is present

Initial Conditions: Wind Case

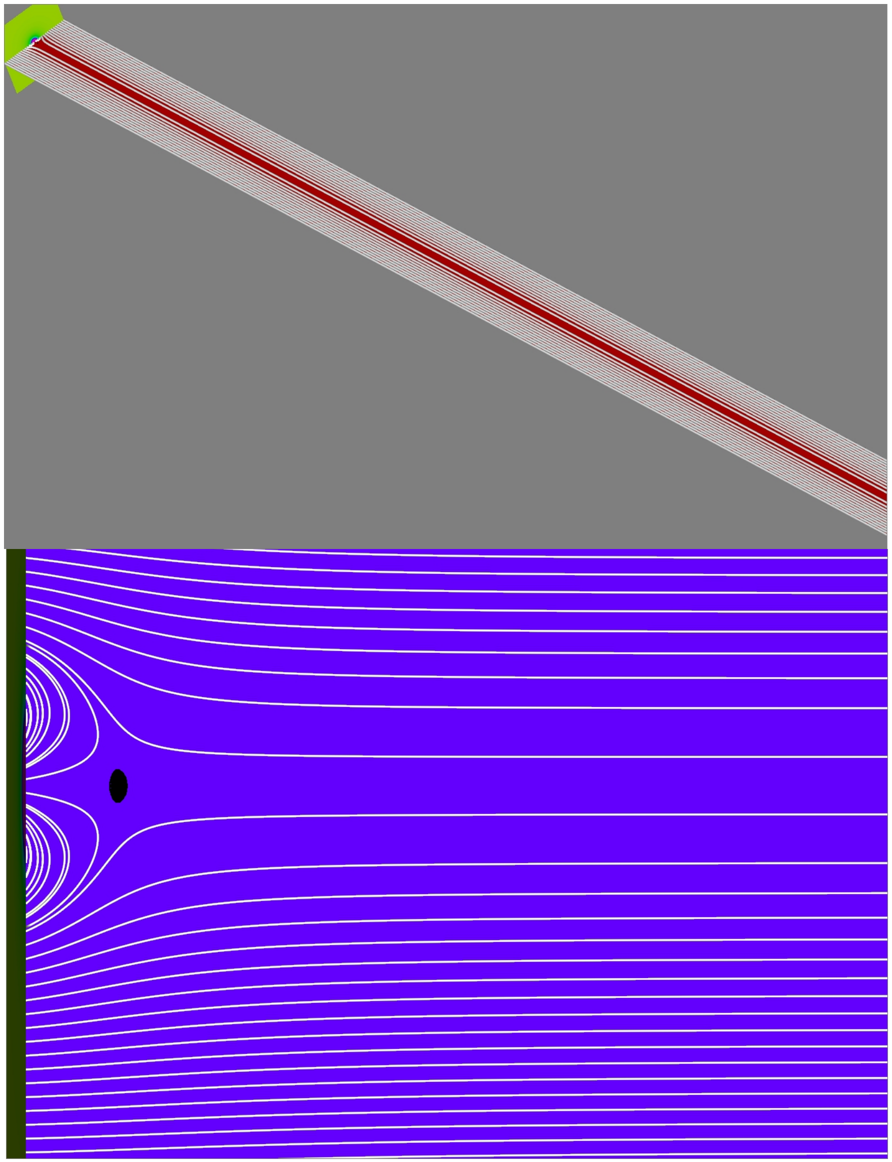




- Computational system: outer boundary at 9 Rs, side boundaries at ±9°
- Isothermal (T = 1 MK)
- Inner jet-source region has radius ~22 Mm and null point height ~15 Mm

- Top: total velocity in midplane (r=1 - 5.4 Rs)
- Bottom: Close-up of mass density in midplane (r=1 - 1.2 Rs). Null point is in black blob (isosurface of β=5)
- Both: Magnetic field lines are white

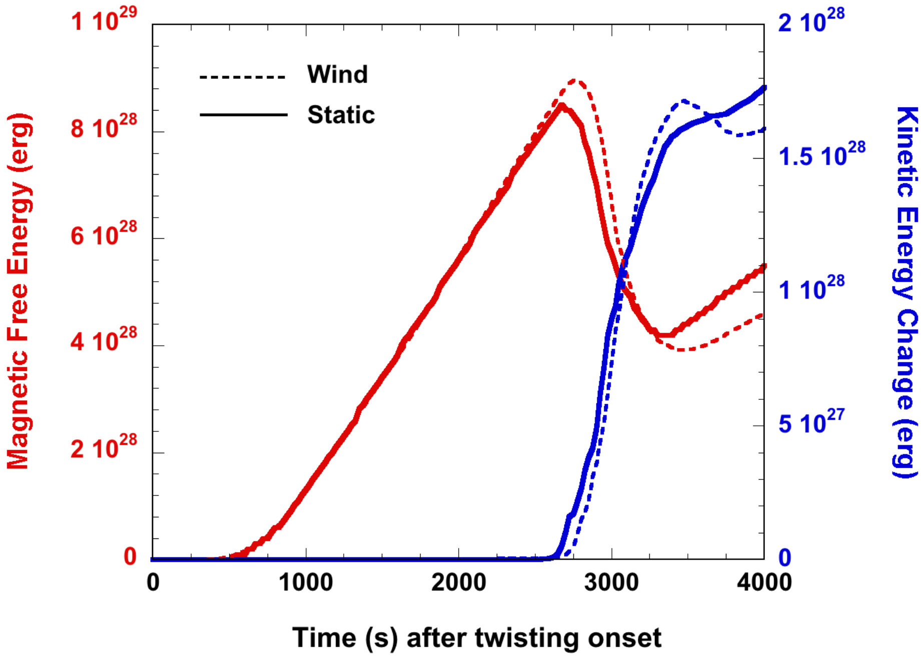
Initial Conditions: Static Case

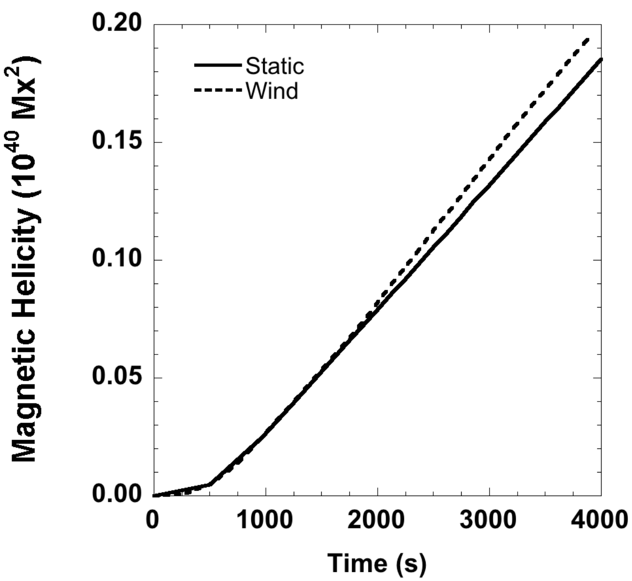


- Computational system: top boundary at 8.5 Rs, side boundaries at ±0.15 Rs
- Isothermal (T = 1 MK) and uniform density (2 x 10^{-16} g cm^{-3})
- Inner jet-source region has radius 20 Mm and null point height 15 Mm

- Top: total velocity in midplane (r=1 - 5.7 Rs)
- Bottom: Close-up of mass density in midplane (r=1 - 1.2 Rs). Null point is in black blob (isosurface of β=5)
- Both: Magnetic field lines are white

Energetics and Helicity



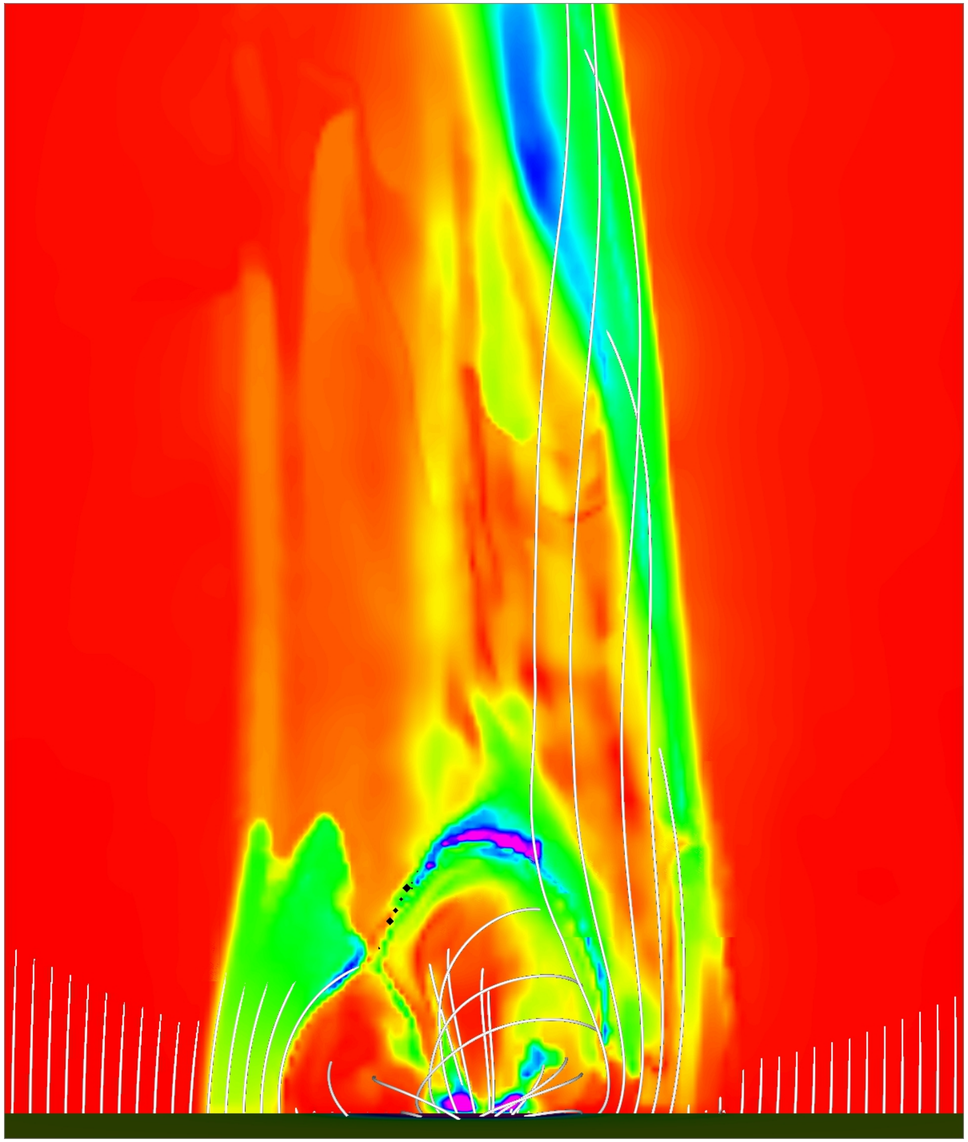


- Magnetic free energies reach almost the same peak value.
- Static case reconnects earlier and releases less magnetic energy.
- At the end of both runs, both cases are on the way to ejecting another jet (MagE is rising), because the systems are still being driven
- Global properties do not reflect the key differences that show up clearly in the local properties.
- Magnetic helicity continues to rise throughout the runs as driving remains steady.
- Wind case builds up slightly more helicity.

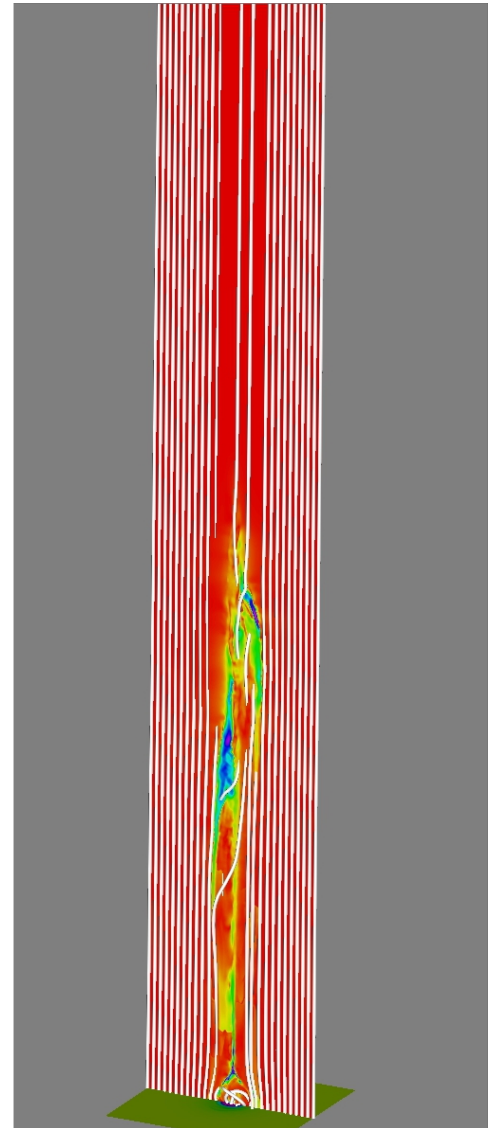
Properties at 4000 s

Properties at 4000 s	Static case (Cartesian, no wind)	Wind case (spherical, wind)
maximum height (Rs)	1.9	5.0
maximum speed $\lvert V\rvert$ (km s^{-1})	630 at 1.8 Rs	4170 at 4.3 Rs
maximum $\lvert V_\varphi\rvert$, $\lvert V_\theta\rvert$, $\lvert V_r\rvert$ (km s^{-1})	$\lvert V_r\rvert=400$, $\lvert V_\theta\rvert=490$, $\lvert V_\varphi\rvert=410$	$\lvert V_r\rvert=3250$, $\lvert V_\theta\rvert=2400$, $\lvert V_\varphi\rvert=2700$
maximum upstream V_A (km s^{-1})	500	2400
maximum jet width (3σ above $\lvert V_{min}\rvert$)	104 Mm at 1.7 Rs = 15.7°	9.3° at 4 Rs ≈ 145 Mm
max. density contrast (ρ/ρ_{bkgd})	1.7 at 1.37 Rs, 1.03 at 1.4 Rs	2.8 at 1.4 Rs, 1.2 at 4.2 Rs
Jet onset (s after twist onset)	2675	2750
Total Energy Change (erg)	$+7.7 \times 10^{28}$	$+7.6 \times 10^{28}$
Peak/Post Magnetic Energy (erg)	8.5×10^{28} / 4.2×10^{28}	9.0×10^{28} / 3.9×10^{28}
Kinetic Energy at $MagE_{post}$ (erg)	1.5×10^{28}	1.7×10^{28}
Max. Injected Helicity Flux (Mx^2 s^{-1})	5.2×10^{35}	5.2×10^{35}

Dynamics: Static Case at 4000 s

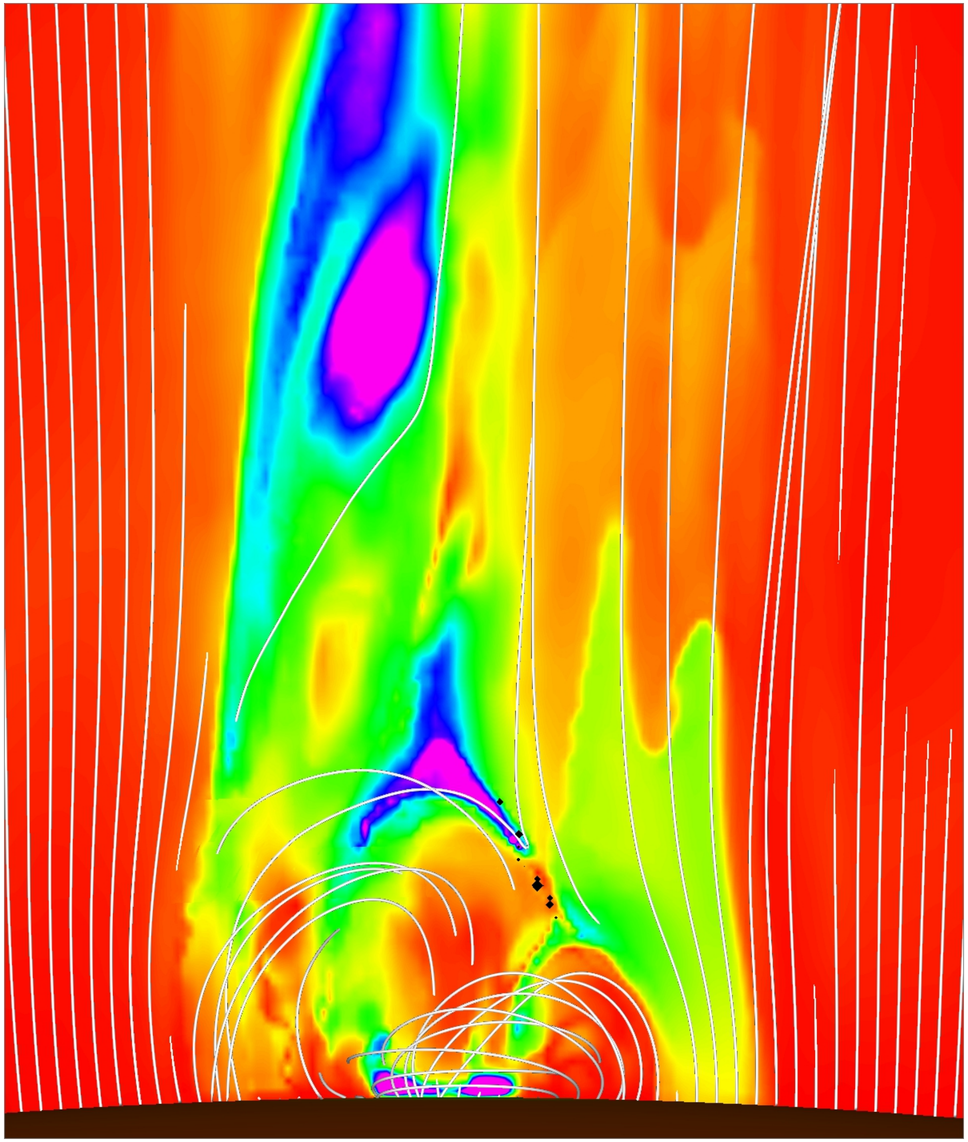


Close-up view of |V| (saturated at 500 km/s)
R = 1 – 1.19 Rs

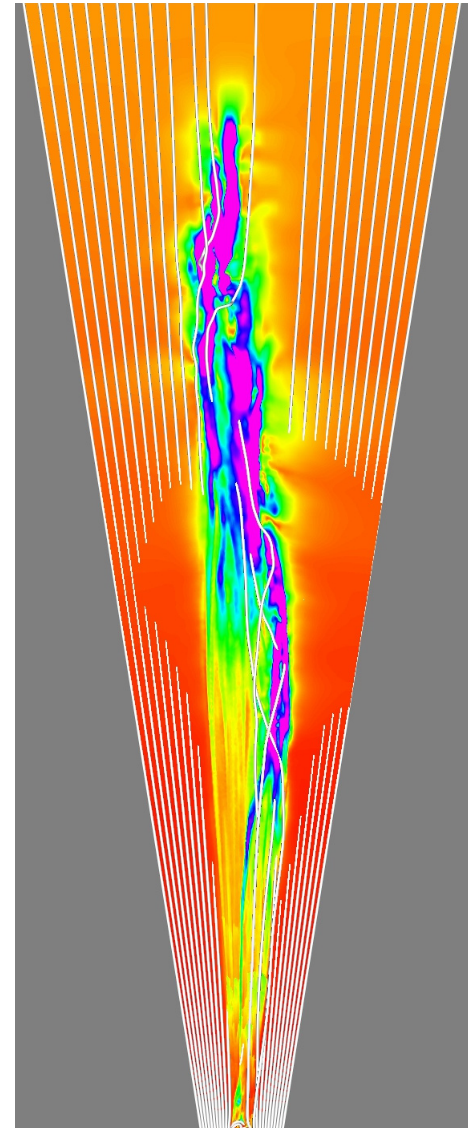


Zoomed-out view of |V|
R=1 - 1.9 Rs

Dynamics: Wind Case at 4000 s

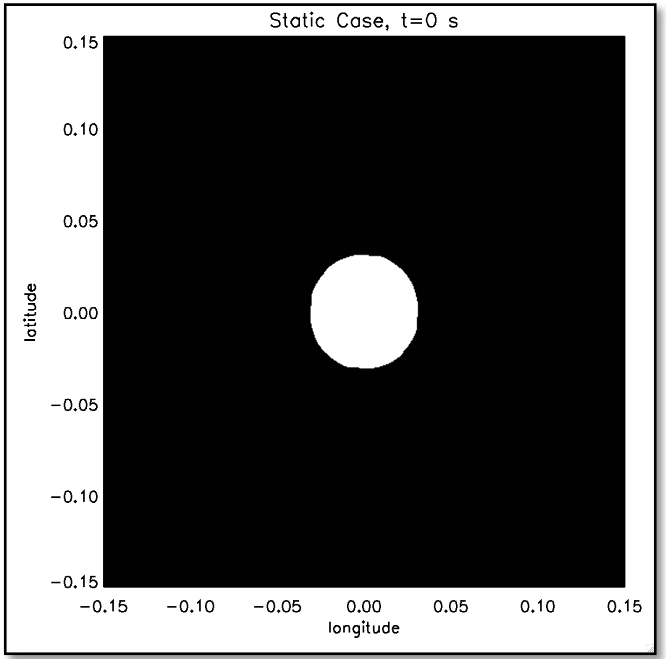


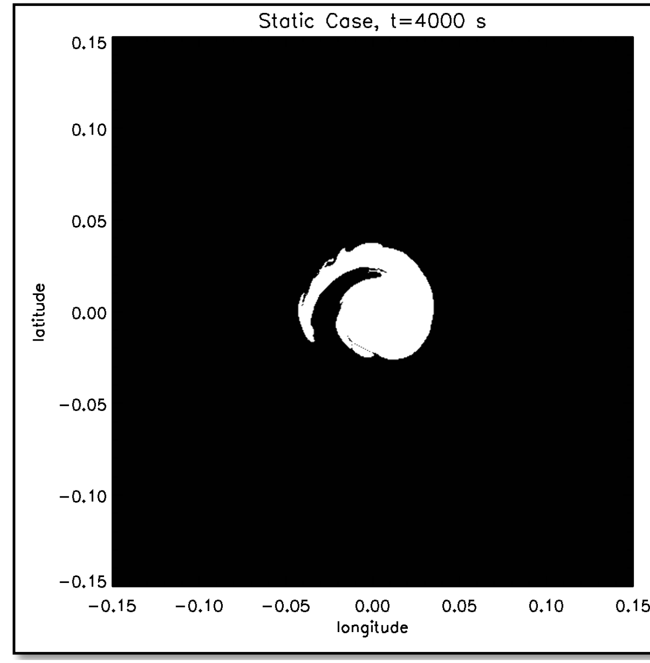
Close-up view of |V| (saturated at 500 km/s)
R = 1 – 1.17 Rs



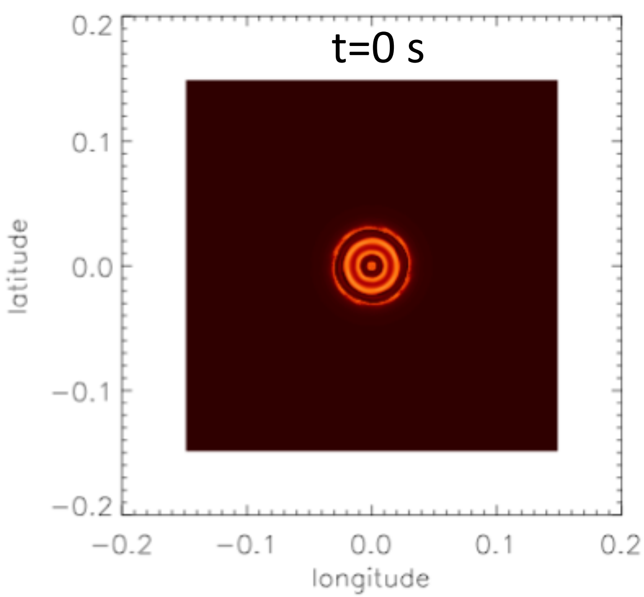
Zoomed-out view of |V|
R = 1 – 5.4 Rs

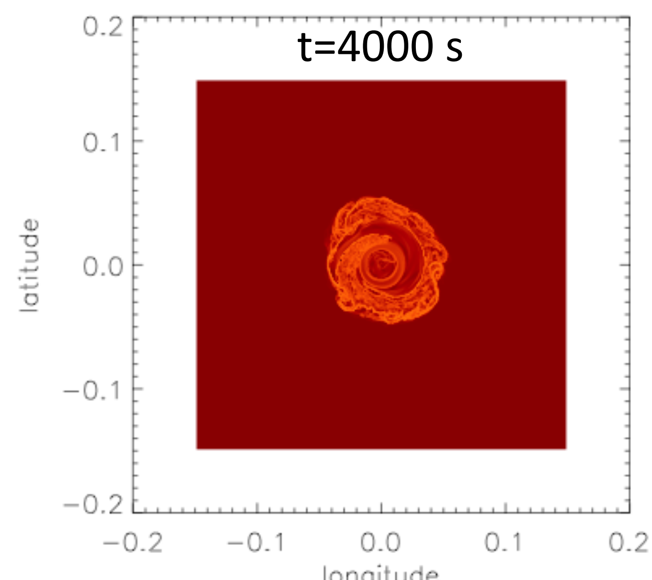
Changing Topology





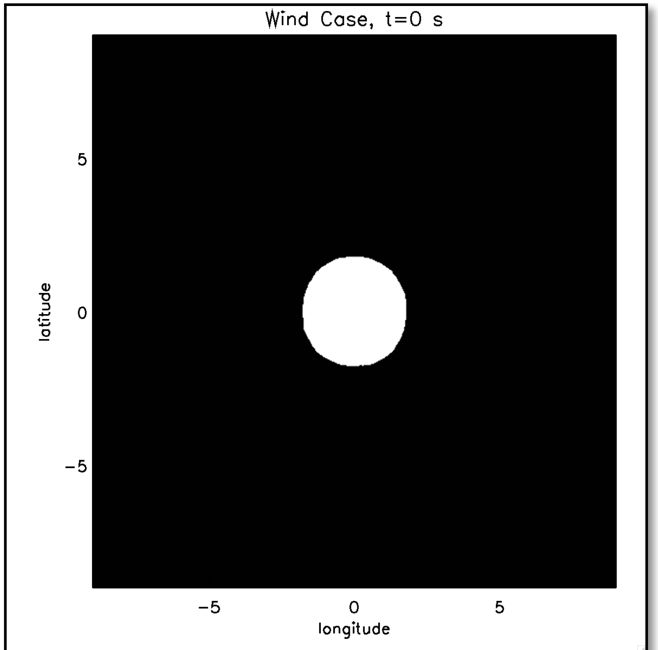
Connectivity map:
Open field = black,
closed field = white





QSL map at base:
Lighter color =
stronger current
layer (QSL)

Changing Topology



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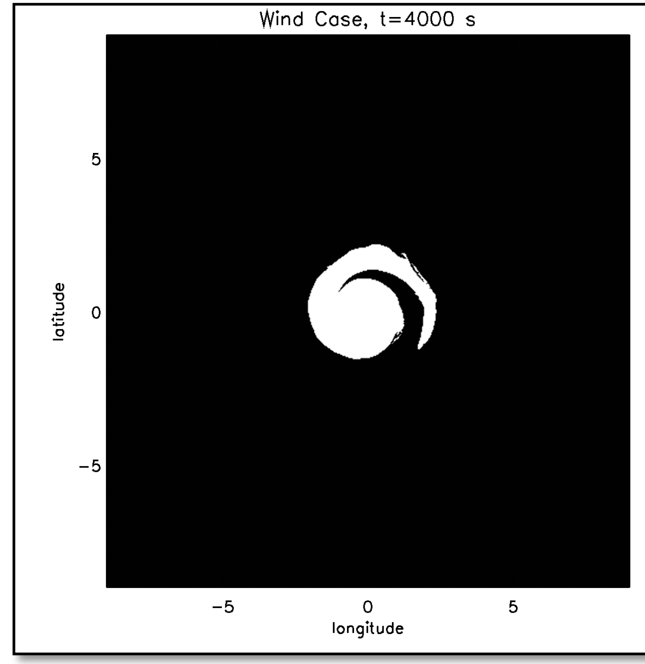

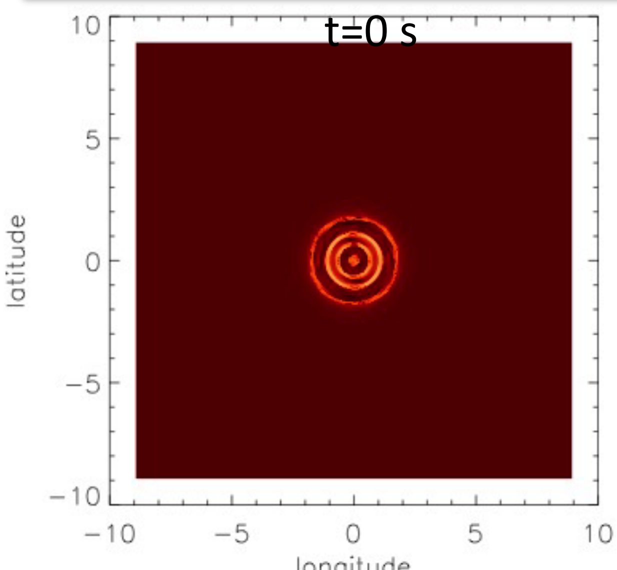

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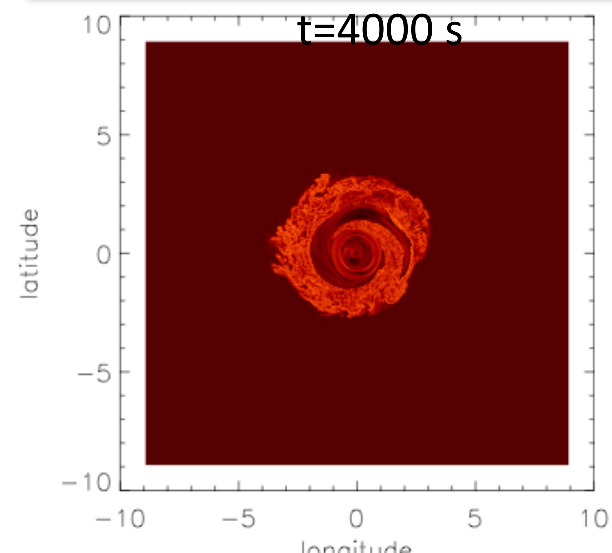
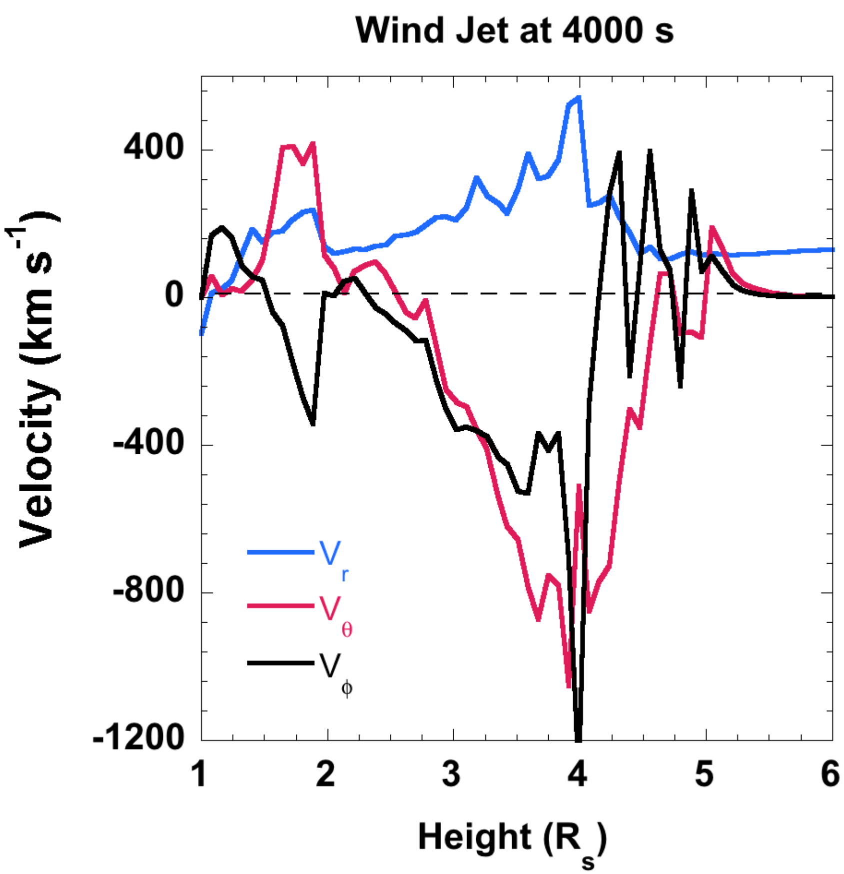
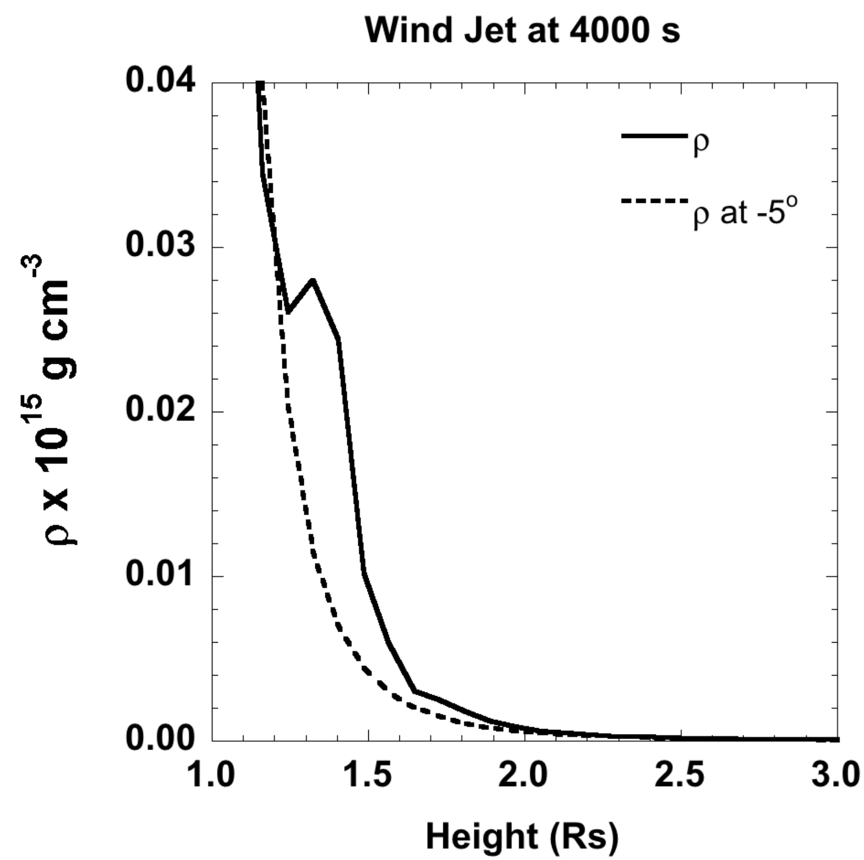


Wind Jet at 4000 s





Note: These cuts along center line (ϑ,φ=0) miss locations of peak torsional flows and density. Jet is fully 3D and "hollow"!

Summary

- We have validated that reconnection is a viable mechanism for driving polar jets in spherical geometry with solar wind. The same mechanism also works for active-region jets (see talk #407.03).
- The magnetic free energy is released primarily as torsional Alfvén waves and collimated but helical Alfvénic outflows. Largest density increase lags well behind waves and fast flow, but effects are still significant far from the surface.
- Current filamentation inside and outside initial fan separatrix is likely to yield heating and emissions.
- Fine structure in jet down to resolution scale indicates current sheets and possible turbulence (see poster 203.02).
- Ongoing runs with larger domain (not shown) exhibit jet/waves extending beyond 15 Rs – well past closest solar approach of Solar Probe Plus.

Future Modeling Extensions

- Magnetized anisotropic heat conduction
  - First step beyond adiabatic and isothermal assumptions
  - Connects observable activity at base (e.g., heating and flows) with jet activity above
- Optically thin radiative losses
  - Important energy sink in corona
- Background volumetric heating
  - Simple model to balance radiative losses